Chapter 2
Silica Optical Fiber Sensors Production Methods

The concept of OFS is not new and has been around since the 1960s, but OFS has made the big leap to practical implementation, only thanks to the advances in modern low-loss optical fibers, although some trails using low-loss optical fibers were shown in 1970s [1, 2]. The field of OFS owes its advancement to the progress achieved in the general field of optical fiber and optoelectronic instrumentation. Specifically, the advancement in the field of optical fiber communication systems—such as viable key components: light sources and photo detectors—has helped bringing the costs of OFS systems significantly down. The low cost of sensors is one of the main drivers for the interest in the concept of optical fiber sensing and will be a key issue in the argument of adopting OFS in the concept of IoT, with a wide range of applications [3–5].

Having introduced the concept of optical fiber sensing and the different types of available optical sensing techniques (i.e. modulation/demodulation) in the previous chapter, this chapter moves to the details of the different production methods of Silica OFSs.

The chapter discusses the production methods of the five different types of sensors (previously introduced in Chap. 1), namely Intensity sensors, Phase Interferometer sensors, Wavelength sensors, Polarization sensors, and Distributed Optical Fiber sensors. Each type of sensors will be described in a separate section, with subsection describing the production methods and another subsection listing the most typical application of such type of sensors. The sections will further address the complexity of the production process, analyzing and comparing the sensitivity and accuracy of different types of manufactured sensors.

This chapter can be used as guidelines for readers, who are trying to decide which production method to use for their applications and requirements.

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2.1 Intensity Sensors

The first type of sensors discussed is the Intensity-modulated sensors, which is amongst the earliest OFSs studied. Basically, the concept of Intensity-modulated sensors depends on modulating the intensity of light passing through the fiber by various means including bending, reflectance or changing the medium. The attractive attributes of such type of sensors are its ease of fabrication, simple detection method and low-cost [4, 6, 7].

2.1.1 Production Methods

In the previous chapter, different techniques of intensity-modulated based fiber sensors have been presented, such as fiber displacement, transmission loss, reflective, and evanescent field. This subsection will discuss the production process of those different techniques.

The first technique is fiber displacement sensor, in which two optical fibers are connected in series. The light source and the detector are connected at either side of the optical fiber. When any movement or displacement, either in transverse, longitudinal angular or differential direction occurs between the two fibers, the light intensity received by the detector changes [8], as shown in Fig. 2.1.

In a reflective intensity sensor, the fibers for the input and output optical signal are placed in parallel configuration with each other (in a two fiber parallel coupling configuration), while the target object is placed in a close distance to the fiber ends, as illustrated in Fig. 1.7a of Chap. 1. The target object reflects the light depending on the distance from the fiber end and the interaction of the reflective material with the incident optical signal. The optical fiber connected to the optical signal analyzer (OSA) detects the changes of the reflected optical signal [4, 8].

Another intensity sensor can be built based on the modulation of the transmitted light by the optical fiber, by inducing a bend on it. The measured parameter causes a bending in the fiber, which results in changes in the light intensity of the output signal. Any physical action able to induce or change a bend in the optical fiber can be monitored using this technique. There are two types of fiber bending, namely Microbend and Macrobend.

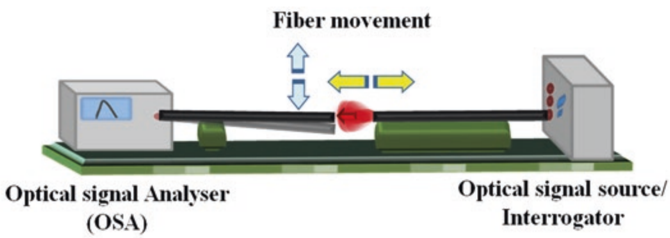

Fig. 2.1 Schematic diagram of a displacement intensity sensor

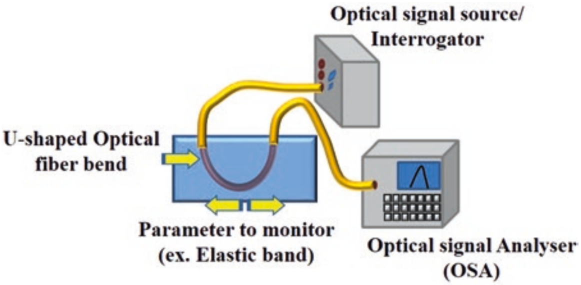

Fig. 2.2 U-bend sensing configuration based on macrobending

Microbend based sensors are used in applications where the measured parameter such as strain, pressure, or force can be mechanically attached and related to the movement of platforms that can induce microbends in the optical fiber [9]. The sensing fiber is placed in between teeth-like deformers to trigger the optical fiber loss. In that way, the sensor probe senses the measured parameter, which is induced by decreasing the distance between the upper and lower teeth, resulting in a series of bend formation along the length of the fiber [9]. The continuous movement of the grooved platform can be linearly related to the optical signal loss in the output fiber end. This mechanism was illustrated in Fig. 1.5 in Chap. 1.

The second type of bending is the macrobending technique. Contrary to microbending, no deformer is required to change light intensity in the macrobending process. In macrobending, the fiber is shaped into U-shaped, round loop(s), sinusoidal shape or other comparable bending formations, which permit attenuation in light intensity, as represented in Fig. 2.2.

The fiber sensing section is then placed in contact with measured parameter, which by altering the radius of the sensing fiber will induce changes in the light intensity that is received by the light detector. The change in the intensity of the output optical signal will be a function of the value shift of the parameter [8, 10].

The last type of intensity sensor is the evanescent field sensors, which is a phenomenon characterized by the fact that the optical signal along the fiber is not totally trapped in its core (for incidence angles near to the critical angle), but some signal leakage can occur into the surrounding medium, more specifically into the cladding [11].

The design of optical fiber is made for the optimum signal propagation with minimum loss possible. Nevertheless, when sensing is involved, it is essential that the optical signal interacts with the surrounding environment, in order to monitor its parameters.

To boost the interaction of the optical signal propagating in the fiber with its boundary, the evanescent field of the transmitted light should be exposed, which can be achieved by reducing or removing part of the optical fiber cladding. Once the cladding is removed, and the substrate is placed in contact with the optical fiber, the parameters under analysis can be detected through the leakages created by the absorption of the evanescent field, which modulates the optical signal intensity [3, 11, 12].

In this simplistic design, the penetration depth of the evanescent field is not enough for an accurate and efficient sensing [3, 12]. In order to optimize this sensing mechanism, research efforts have proposed solutions such as the use of macro-bending, optical signal input angle shift, fiber tapering or the use of special fibers like D-shape fibers or microstructure fibers [13–17].

2.1.2 Typical Sensing Applications

Optical fibers are intrinsically safe for human use in the field of healthcare, due to their chemical inertness and non-toxicity, in addition to their dielectric nature and tiny size, which make them suitable for miniaturized devices or embedment into textile materials for sensing. Such characteristics of optical fibers have motivated extensive research of using high sensitive intensity based OFSs in physical, structural, biological, chemical and biomedical fields [4].

For instance, microbend OFSs have been explored, with good performance, for the monitoring of parameters such as pressure, temperature, strain, vibration, acceleration, displacement, humidity, pH, and in the monitoring of breath rate and respiratory/body movement [7, 18–21]. The main advantage of microbend OFSs over other OFS types is their design simplicity and low production costs.

In the rest of this subsection, different specific examples of health monitoring applications, which have been discussed in literature, will be presented, highlighting sensing configuration and advantages.

Low back pain (LBP) is one of the main health issues associated with the lumbar spine (part of the spinal column between the thorax and sacrum), and its diagnosis and rehabilitation procedure requires accurate assessment of the lumbar spine condition. For such precise diagnosis, Dunne et al. suggested using OFS for monitoring the lumbar spine in [8, 21]. They used an optical fiber bending sensor, which was attached to a wearable textile outer surface allowing the sensor to move vertically. They placed the optical signal source and a detector at either end of the fiber. The intensity of the output optical signal was modulated according to the degree of the bend in the fiber, which is directly correlated to the curvature of the lumbar spine [21].

Other approaches, based on intensity modulated, use a series of coupled fibers along the spinal, which modulates the spinal angle movements by monitoring the light intensity output [22]. Also using the coupling efficiency between two optical fibers, it is possible to monitor the upper limbs. The misalignment between two coupled fibers can be related to the angle of the joint movement [8].

Similarly, for the monitoring of the lower limb, different sensing solutions have been used. For instance, Bilro et al. presented an optical fiber technology based on the microbending effect to monitor the gait movements. In this approach, the fiber is placed along the knee joint in vertical alignment, while the optical signal source and the output detector are placed at different ends of the fiber. The knee movement is then measured by recording the light attenuation, which occurs due to direct fiber bending [23]. This technology is neither as bulky as similar inertial gait sensors, nor as expensive as video monitoring approaches [8].

OFSs are also applied for another health monitoring application, namely respiratory monitoring, where macrobending intensity modulation effect is used [7, 24–26].

In those approaches, configurations such as U-shape bent fiber or fiber shaped in sinusoidal form with a concentrated distribution, imbedded in a textile elastic belt (to be placed at the patient thoracic area), are used to monitor the respiration rate associated to the abdomen movement [24, 25].

Nevertheless, this approach still presents some drawbacks, such as uneven force distribution, un-proportionality between the bending loss and the number of loops in fiber and the fiber bending radius dependence on the optical signal input wavelength [26].

From a signal point of view, heart rate is similar to respiration rate, except for the frequency. The frequency of human heart beat lies in the range of 0.7–1.8 Hz (40–110 beats/min), while the respiration beat is much lower lying in the range of 0.2–0.5 Hz (12–30 beats/min) depending on the person age. Having such similarity, same (or at least very similar) sensing methods can be used for heart rate monitoring [8].

Finally, it is worth mentioning that the type of fiber has significant effects on the cost, performance and other handling concerns for the sensor implementation. One issue, related to the macrobending technique described in the applications mentioned above, is the difficulty to distinguish between normal and abnormal bending of fiber during the monitoring process. One possible solution is to implement the optical time-domain reflectometry (OTDR), which is able to monitor the loss distribution along the fiber length [8].

Besides its biomedical applications, intensity based optical fiber sensors also paved their way into other differentiated fields, such as the Structural Health Monitoring (SHM).

In the SHM field, this technology is applied for the monitoring of buildings, bridges, tunnels, wind turbines, railway, geotechnical and highway structures, pipelines, among others [27, 28].

Also, chemical parameters and solution elements can be monitored based on intensity OFSs. For instance, a flexible and accurate evanescent wave technology based on the cladding lateral polish of the optical fiber with low-cost light sources has been presented for pH, relative humidity and temperature monitoring [11].

2.2 Phase Interferometer Sensors

The second type of OFSs, to be discussed in this chapter, is the Phase-modulated sensors, which are also known as interferometric sensors. Phase Interferometer sensors are built based on the phase difference of coherent light, which travels through two different paths, either in one same fiber or different fibers. Interferometer

Optical Fiber Sensors (IOFSs) are characterized by high-sensitivity, since they are able to respond to the smallest changes in the external measured feature or parameter. Phase interferometric fiber sensors cover multiple types including Mach–Zehnder, Michelson, Fabry–Perot, and Sagnac interferometers [29].

The length of the optical path of each arm of the IOFS, which is a derivate of the fiber refractive index and the fiber geometrical length, can be influenced by environmental physical parameters. This optical path length variation can be precisely measured by optical fiber interferometry. By measuring the phase difference, the change in the environmental physical parameter can be quantified. This is the principal concept of IOFS operation [30].

2.2.1 Production Methods

It is worth mentioning that the nature of the targeted application affects the production of OFSs in general, and IOFSs are no different; hence IOFSs are produced using different techniques, either for discrete, quasi-distributed, or distributed fiber sensing applications. In applications as intruder detectors, where IOFS are produced using distributed or quasi-distributed monitoring, commercial optical fiber can be used. This commercial optical fiber is basically the same as the one used for optical fiber communications. In many applications such as for temperature, fiber optical gyroscope (FOG) or strain measurements, no special optical fiber is required [30].

Not only the optical fiber depends on the application, but the jacketing and cladding of the OFS have to be designed to suit the specific application. For instance, for strain sensing, the optical fiber cable structure must be resistant to temperature shift and block the heat transfer to the optical fiber sensing element, in order to prevent the temperature influence in the measured strain values [29].

On the other hand, in other applications (bio chemical sensing) based on refractive index change or other different spectroscopy methods, the cladding of the fiber sensor should be completely removed, so the substrate maintains a direct contact with the sensing element. Different methods for removing fiber cladding have been used, including chemical etching by hydrogen fluoride acid and fiber tapering by CO_2 laser or hydrogen torch [31].

As previously introduced in Chap. 1, different types of IOFS include Fabry–Perot, Mach–Zehnder, Michelson, and Sagnac principle based sensors. Owing to their several advantages such as easy alignment, high coupling efficiency, and high stability, IOFSs have been widely investigated for micro-scale and in-line applications [30]. Within the in-line configuration, the sensing element can be intrinsic or extrinsic to optical fiber.

For Extrinsic Fabry-Perot Interferometer (EFPI) fabrication, the cavity is formed outside the optical fiber, by external reflective surfaces. The advantage of such configuration is its easy production method with low-cost equipment; nevertheless, they may present some drawbacks, such as packaging, accurate alignment and low coupling efficiency [29]. To overcome such low coupling efficiency issue, Photonic

Crystal Fibers (PCFs) are used. An FPI cavity can be formed by inducing the air holes for the fiber to collapse, by electric discharge or laser incidence. The collapse of the air holes can easily create a lens at the PCF end, which acts as a reflective surface [30, 32, 33].

In contrast, in the case of Intrinsic Fabry-Perot Interferometers (IFPIs), the mirrors are placed inside the optical fiber itself. IFPIs can become expensive, since they require high-cost equipment for fabrication [29]. Nevertheless, new low-cost solution has also been reported for the production of inline FPI microcavities, only by splicing a standard optical fiber with recycled optical fibers previously destroyed by the catastrophic fuse effect, which presents a considerable economical solution of optical fiber sensing [34, 35].

Among the interferometric OFSs, sensors can be based on a resonance or on a non-resonance mechanism. One sensor based on resonance is Sagnac resonators, which operate on the principle of constructive and destructive interference. The resonance frequency varies according to the changes in the monitored environmental parameters. The measurement of such resonance frequency is used to monitor the physical parameter under study. The output optical signal contains the amplitude or phase shift at a given frequency, which can provide the information of the monitored surrounding environment [29].

Alternatively, non-resonance IOFSs function is based on comparing the optical path difference (OPD) of the different arms of the optical fiber interferometer (Mach–Zehnder, Michelson based sensors). In such technique, at least two arms are used, while only one of those arms is exposed to the environmental variations. The other arm is placed isolated from the variation, working as the reference arm. The OPD can be easily measured by monitoring the changes in the output optical interference signal. Resonators phase is strongly influenced by the optical length change in the resonance frequency proximity. In order to enhance the sensitivity of a non-resonance IOF, the implementation of resonators in the sensing arm is highly advised [30].

2.2.2 Typical Sensing Applications

Different sensing configurations (from point, quasi-distributed or distributed sensing) are chosen based on the location of the required measurement. Point sensors are used when monitoring a physical parameter at a certain position, while distributed fiber sensors are the choice, when continuously measuring a sensed parameter along the length of the fiber. Finally, quasi-distributed sensors can monitor a physical parameter at finite positions, along the length of the optical fiber. Interferometric OFSs can be implemented in the three different configurations [36].

For a quasi-distributed sensing implementation, some multiplexing techniques are required to be implemented. Different multiplexing techniques can be used, namely frequency division multiplexing (FDM), time division multiplexing (TDM), code division multiplexing (CDM), wavelength division multiplexing (WDM), space division multiplexing (SDM), and hybrid multiplexing schemes [36–39].

The multiplexing schemes (to transmit the output data) are chosen considering features like the number of sensors to multiplex, the sensor frequency response, the dynamic range need, the financial cost, and economic impact [30].

All types of IOFSs are suitable for temperature monitoring. In Mach–Zehnder and Michelson IOF, the reference arm is kept at a given constant temperature, while a sensing arm is deployed at the position where temperature monitoring is required. In-line Mach–Zehnder and Michelson interferometers can also be used as integrated temperature sensors.

When using Sagnac interferometer for temperature sensing, the fiber of Sagnac ring is doped in order to achieve a high thermal expansion coefficient, which induces a high-birefringence shift [29, 30].

Another application, where interferometer sensors are used, is strain sensing. Strain usually induces a considerable variation of the optical fiber dimensions, which lead to strong shift of the refractive index of the fiber (both in the core and cladding) [29]. However, strain sensing OFSs sometime suffer the drawback of mutual sensitivity to temperature. But with the choice of an appropriate fiber protection or its composition, the effect of the variation in both parameters can be efficiently separated. Practically, it is possible to distinguish the different effects and hence produce sensors insensitive to one of the parameters (temperature or strain) [30]. The strain sensing OFSs are adequate to use for many applications including seismographs, hydrophones, geophones, structural health monitoring, etc.

An acoustic OFS, known as fiber hydrophone, is characterized by its high sensitivity and wide dynamic range when compared to conventional piezoelectric (PZT) ceramic sensors. Additionally, optical fiber hydrophones are immune to electromagnetic interference, do not require electronic devices at the monitoring set and can be deployed in a large number. Those features are essential for applications such as seismic exploration for oil reserves. Optical fiber hydrophones are, therefore, the answer to this quest, since they are able to multiplex a big number of sensor outputs on a single optical fiber [30, 40].

IOFSs are adequate to produce both types of strain sensors: in transmission and reflection configuration. Mach–Zehnder interferometers have been widely used in the early optical fiber hydrophone systems, specifically in transmission-type sensor [41]. In contrast, the Michelson configuration is more appropriate for building a reflective fiber hydrophone array. In such configuration, the induced light passes through the sensing arm twice; thus, providing twice the sensitivity of a Mach–Zehnder interferometer [41].

Alternatively, the Fabry–Pérot optical fiber hydrophone is considered the simplest transmission-type strain sensor, which possesses the advantages of being compact, but suffers from small dynamic range [41–44].

Due to OFSs ability to measure strain and temperature simultaneously through multiplexed interferometric, they offer various advantages in structural engineering, both for the quality control during construction process and also, thereafter for monitoring the health of buildings through time. IOFSs have been demonstrated for use in many important structures such as aircraft, marine vehicles, dams, and bridges. Moreover, IOFSs have been also implemented in the electric power industry for remote load monitoring of power transmission lines [27, 34, 35, 45].

2.3 Wavelength Sensors

Moving on towards one of the most commonly investigated type of OFSs, this section discusses wavelength-modulated OFSs. The concept of wavelength-modulated OFSs is built based on the idea of the variation in the propagating optical wavelength (spectral modulation) by an external monitored perturbation. Some of the common wavelength-based OFSs are Bragg grating sensors and fluorescence sensors.

Out of those wavelength modulated OFSs types, Bragg grating sensors are the most commonly used and are considered the most promising development technique [46].

Fiber Bragg gratings (FBGs) are written in optical fibers, by inducing periodic modifications in the optical fiber refractive index [46]. Such modulated periodic structure enables the propagating optical signal to be coupled into a backward propagating core mode, creating a reflection optical signal [46]. This reflected optical signal (reflected Bragg wavelength) is sensitive to a range of physical parameters; hence, FBG-based sensors can be used in a variety of applications [47, 48]. On the other hand, fluorescent-based OFSs are used for different physical and chemical monitoring, including temperature, humidity and viscosity [49].

In the following section, the different production methods of wavelength modulated OFSs are discussed, concentrating on FBGs development due to its popularity. These sensing elements attracted a widespread research level, which boosted its rapid development. Hence, multiple techniques have been elaborated, along with several demodulation techniques [47].

2.3.1 Production Methods

The discovery of FBG modulation had significant impact on the development of optical fiber sensing. Since they were first investigated for sensing purposes in 1989, FBG sensors have gained wide attention resulting in a variety of demodulation techniques for different monitored parameters and diverse applications [48]. Due to its popularity and widespread use in telecommunications and sensing application, the production methods of FBGs are discussed in more details compared to other OFSs techniques.

FBGs in general are very sensitive to any slight perturbation of the fiber in the grating region; hence they have been extensively investigated in the field of optical sensing. The information with regards to the variation in the measured parameter is wavelength encoded [50].

FBGs are usually functioning based on periodic perturbation of the refractive index along the optical fiber core longitudinal axis [47]. The grating structure is inscribed in the optical fiber to form a selective reflective structure for the wavelength, which satisfies the Bragg condition.

When an optical source is used to illuminate the FBG, only a narrow band spectral component, corresponding to the Bragg wavelength of the grating (λ_{Bragg}), is reflected, whereas all the rest of wavelengths outside the reflection band are allowed to pass [47, 50].

The fabrication of FBGs has passed through multiple phases to reach its current state. In 1981, Lam and Garside mentioned that the mechanism of the formation of FBGs was basically due to the interaction of ultraviolet (UV) light with defect states of the doped silica core [47, 51]. Later on, it was shown that any change in the refractive index could be induced in all germanium-doped optical fibers. This finding has opened new doors in the manufacture of FBGs, resurrecting the interest in its research activity [47].

However, it took almost a decade till another breakthrough in FBG inscription occurred. The technique popularly known as the external inscription technique of writing FBG, was demonstrated by Meltz et al. [47, 52].

In this approach, a 244 nm beam is used, which is split into two and recombined to create an interference pattern at the photosensitive fiber core. The interference pattern induces a punctual and permanent change in the core refractive index [52].

The period of the interference pattern and the refractive index change are determined by the angle between the two split beams, which can be adjusted to produce gratings according to the desired reflected Bragg wavelength [48, 52].

Alternatively, FBGs can be written using phase masks [53]. A Phase mask is made of period patterns usually etched onto fused silica [47]. In such configuration, when the UV radiation hits the phase mask, the zero-order diffracted beam is almost totally suppressed (less than 3% of the transmitted power), while the diffracted orders +1 and −1 are maximized (>33% of the transmitted power) [53]. Figure 2.3 shows the schematic setup used to write FBGs using a phase mask.

Another more flexible method for inscribing Bragg gratings into an optical fiber is the *point-by-point* method. This method uses an UV source, which is passed through a slit and focused on the fiber to induce a refractive index change at a certain location. The fiber is then shifted a distance "Λ", which matches the period of the Bragg condition [47, 54]. However, Point-by-point technique cannot be applied for first-order gratings, due to its submicron translation and tight focusing requirements. Basically, the length of the grating needs to be considerably small and research efforts have only managed to produce second and third-order gratings, like the work of Malo et al. [47, 54].

There are multiple methods for producing grating fringes in optical fiber, using different photosensitive mechanisms. The underlying photosensitivity mechanism is referred to as the *type of gratings*. The method used to create the grating fringes greatly affects the physical attributes of the produced grating, specifically temperature sensitivity and resistant to elevated temperatures. According to current literature, five types of FBG exist with different photosensitivity mechanisms, namely Type I, Type IA, Type IIA, Type II, and regenerative grating [47].

Type I regime depends on the monotonic increase in refractive index modulation of a grating using UV exposure. The growth dynamics of this type of grating can be described by a temporal evolution of the refraction index [55]. Although the inscrip-

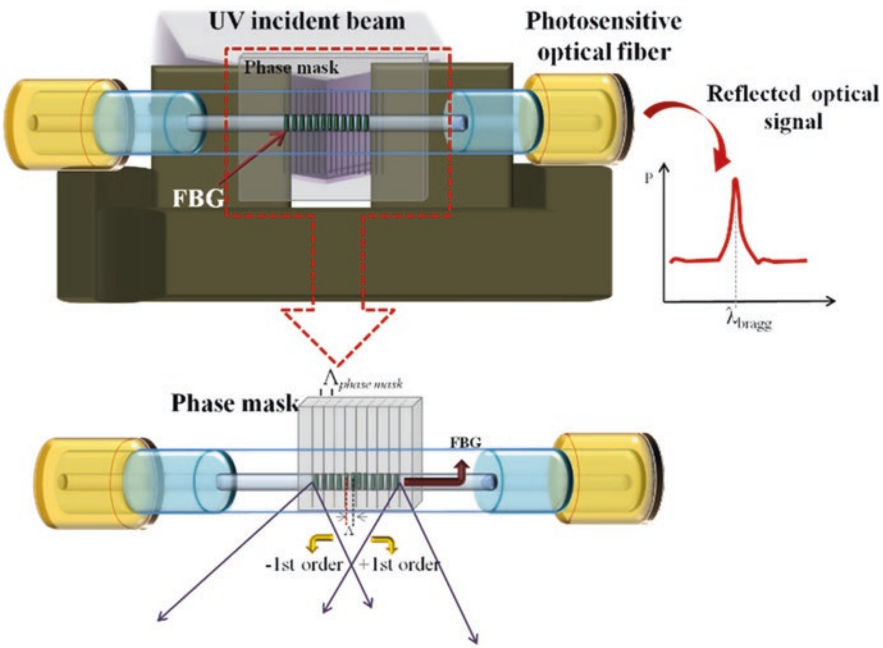

Fig. 2.3 Set up typically implemented to inscribe FBG sensors in photosensitive optical fiber

tion process is quite simple in photosensitive optical fibers, Type I gratings present a low thermal stability [47]. For temperatures below 300 °C, the grating modulation remains constant, but it starts decaying for higher values of temperature.

Type IA gratings are basically a derivate of Type I gratings. They are simply produced through exposing a standard grating in hydrogenated germane-silicate fiber to a prolonged UV beam [56]. Type IA gratings have the lowest temperature coefficient, when comparing with other grating types; hence, they are ideally adequate for temperature compensating in sensor applications.

Type IIA FBGs are similar to Type I gratings, when it comes to spectral characteristics. The gratings require a long process for inscription, which is usually done following Type I grating inscription [38]. Contrary to Type I, Type IIA gratings are more stable at temperatures up to 500 °C [47].

Type II Bragg gratings are produced using excimer lasers, with very high pulse (>0.5 J/cm^2) [57]. The concept is based on the idea that a sudden sharp increase in the refraction index happens, once the power of UV light passes a certain threshold. Such sharp index change, known as Type II, results in the highest stability at extreme temperatures up to 800 °C [47].

The last type of gratings explained here are the Regenerated gratings. The Regenerated gratings can be produced by annealing gratings of Type I; hence the name Regenerated. The regeneration process should occur at temperatures higher than 500 °C. Regenerated gratings are more similar to Type II gratings and they can be repeatedly cycled to very high temperatures without degradation [47, 58]. Recent findings have shown that this method can produce gratings, which are able to operate at extreme temperatures, as high as 1295 °C, outperforming even Type II gratings. This performance presents an extremely attractive solution for ultrahigh-temperature applications [58].

Additionally, FBGs can be classified depending on both the grating periodicity and refractive index. The most common category of FBG is the uniform grating, which has a constant grating pitch. The grating period is typically in the range of 0.25–0.5 μm, with the light coupled into the backward propagating direction. This type of grating is an excellent temperature and strain sensing [47]. Another type of FBG is the tilted grating, which has phase fronts tilted with respect to the fiber axis. In such configuration, the angle between the grating planes and fiber axis is less than 90° [47, 59]. These gratings allow the coupling of light into the cladding into backward propagating radiation modes. Based on its characteristics, the tilted grating is usually used in erbium-doped fiber (EDF) amplifiers for gain equalization [47].

Moreover, the chirped grating has a non-periodic pitch, which displays a constant increase/decrease in the grating planes spacing. Chirped grating is used in multiple applications in both telecommunications and sensor fields, including dispersion compensation [47, 60].

Finally, to conclude the discussion of the production of FBG sensors, it has to be mentioned that FBG sensors have one basic and very important trait, which is the differentiation between the effects of strain and temperature. Generally speaking, temperature and strain have very similar effects on Bragg wavelength shift. It is very important to isolate the effects of temperature variation (when monitoring temperature) from effects of other physical parameters, specifically strain, and vice versa. This motivated many techniques to be developed over the years to discriminate the effect of strain and temperature. Two main categories have been defined in the industry for temperature-compensating methods, namely, extrinsic and intrinsic methods. As the name implies, extrinsic method use external material, which is usually combined with the grating to compensate the temperature, whereas obviously intrinsic methods use certain properties of the optical fiber itself [47].

2.3.2 Typical Sensing Applications

Having discussed the production processes of wavelength based OFSs and specifically FBGs, this sub-section goes over the most common sensing applications of wavelength-based OFSs. Wavelength-based OFSs, and specifically FBGs, are famous for strain, temperature and vibration sensing. Strain sensing is usually used to monitor other physical parameters.

The first application to be discussed and one of the most important uses of Bragg gratings is strain monitoring, whether static, quasi static, or dynamic.

For strain sensing, FBGs are written on the core of a conventional single-mode optical fiber. When applying strain along the longitudinal axis of the fiber at constant temperature, the Bragg wavelength shifts due to the change in the grating periodic spacing and the induced photoelastic variations in the effective refractive index of the optical fiber core [47].

FBG based sensors present a linear dependence between the strain and the reflected Bragg wavelength shift of the sensing element, within the elastic deformation limit of the fiber [47]. Also, the sensitivity of the produced FBG sensor is highly dependent on the photosensitivity of the fiber used in the production of the FBG, in addition to the fiber diameter [47].

Although strain is the direct measurable parameter, strain sensing FBGs can be employed to indirectly measure force, displacement, vibration, pressure, liquid level and flow dynamics, and magnetic field.

One major application of FBGs is vibration sensing, which is highly adequate for structural health monitoring (SHM) and damage detection [61–63]. These vibration sensing systems operate in two distinct themes: (a) Single-point system, which monitors localized region and (b) Quasi-distributed sensing system, which provides sensing capabilities along the whole length of an optical fiber [47]. Vibration sensing FBGs provide low-frequency and high-frequency response, which are adequate for different applications based on their nature. As for low-frequency response accelerometers, they are best suited for large structures such as bridges, towers, dams, etc., due to their low inherent frequencies. High-frequency response vibration sensors with high spatial resolution are widely used for crack detection of materials, where the frequency of such events could be elevated [61–64]. The concept of FBG vibration sensor is based on the fact that vibrations induce high-speed dynamic strain variations in the FBG sensing element; hence, by monitoring the shift of the Bragg wavelength the measuring of such vibrations is made possible [61–64].

As previously mentioned, FBGs are also highly sensitive to temperature and therefore they are widely deployed specifically in harsh environments due to their high resilience [47]. The thermal-induced changes in Bragg wavelength occur due to two factors. First, temperature changes result in the variation of the effective refractive index of the optical fiber core guided mode and second, the variations in temperature modify the grating period [47, 49].

Typical temperature responses are 6.8, 10, and 13 pm/°C for the Bragg wavelength of around 830, 1300, and 1550 nm, respectively [47].

Although mentioning FBGs always indicates permanent refractive index modulation in the fiber core, it was shown that extreme high temperature environments may cause the refractive index modulation to be erased. The maximum tolerated temperature recorded for conventional FBG sensor is around 600 °C, basically due to the weak bonds of germanium and oxygen of the fiber core material [47].

It is reported that thermal stability of the gratings is directly dependent on the composition of the fiber core used for the writing of the gratings. Despite the intolerance of conventional FBGs to extreme high temperatures, special compositions of optical fibers dopants have been proposed to create FBG temperature sensors sustainable up to 1000 °C [65–69]. Some examples of those successful efforts include gratings in fluorine-doped fibers, gratings written into N-doped fibers [65, 66], regenerated gratings [69], and the use of femtosecond IR lasers for the gratings inscription [47, 65–67].

Humidity is another critical physical parameter that is usually required to be monitored constantly in certain applications. This parameter, and its accurate control, is highly important in air conditioning maintenance for human comfort, fighting bacterial growth, and also in the in quality control process of certain products, etc. Humidity is defined as the amount of water in gaseous state present in the atmosphere of a certain environment. A more important term is the relative humidity (RH), which is defined as the ratio of the amount of water vapor actually existing in the environment to the maximum possible amount that the same environment can carry [68–70].

RH sensing using a polyimide-coated FBG was proposed by Kronenberg et al. [70]. The concept is based on the fact that the polyimide polymers, being hygroscopic, tend to absorb moisture and swell in damp atmosphere, as water molecules migrate into their material. The swelling of the polyimide coating is used as a stimulator to force strain on the FBG-containing fiber. Clearly, such strain modifies the Bragg conditions; thus varying the Bragg wavelength accordingly, which is monitored to keep track of the RH [47].

Optical fiber gas sensors have been designed to detect hazardous gases. Nowadays, Hydrogen is turning into an attractive alternative energy source for clean-burning engines and power plants, or even in critical applications, such as the Space Shuttle main engine. Unfortunately, the use of highly flammable liquid H_2 does not come without its own risks. Using such highly flammable fuel introduces safety hazards, due to its low explosive limit and rapid evaporation rate. Those risks attracted some efforts to design and propose OFSs to detect the leaks in hydrogen-fueled systems [47]. To control Hydrogen based processes, Butler and Ginley proposed a technique for sensing hydrogen leaks [71]. They built their design on the realization of the change in the elastic property of Palladium (Pd) during Hydrogen (H_2) absorption. Their model can be used to determine the axial strain in the fiber core. The sensing technique is based on tracking the induced mechanical stress in the palladium coating, as it absorbs H_2. The fiber is stretched by the stress induced in the palladium coating, thus expanding the grating period, which shifts the FBG Bragg wavelength [71].

2.4 Polarization Sensor

The concept of Polarization sensor is mainly based on the change of the state of polarization of the light wave propagating through the optical fiber. Such state change occurs due to the difference in the phase velocity of the two polarization components in a bi-refringent fiber. Different factors can vary the polarization properties of optical signal travelling in a fiber, including strain, pressure, stress and temperature. In polarimetric OFSs, the change in the state of polarization is monitored and used to access a specific sensing parameter [72, 73]. In the rest of this section, the details of the fabrication process of polarization OFSs are discussed, along with the most widely used applications.

2.4.1 Production Methods

As initially stated, polarimetric OFSs typically use high birefringent (HB) optical fibers, such as *bow tie* fiber, *panda* fiber, or elliptical core or polarization maintaining PCF fibers [74]. HBs are produced with high internal birefringence, which is achieved through engineering the core and/or cladding with an elliptical geometry, or by inducing an anisotropic stress into the cross-section of the fiber [74].

This physical structure of the fibers allows the phase velocities difference for the two orthogonally polarized modes to be big enough, to avoid the coupling between these two modes [74].

HB fibers, under external deformations, present the lowest order modal behavior, which is of special interest for sensing applications. However due to the high sensitivity of polarimetric OFSs to external parameters, such as strain and temperature, cross sensitivity is usually a major issue. As has been mentioned in the case of Phase Interferometer sensors, differentiation between sensitivity to different external factors has to be addressed during sensor design and application [74].

In a typical polarimetric sensor, polarized light is inserted at 45° into the main axes of a birefringent fiber, such that both polarization modes become equally excited. The polarizer analyzer (with a 90° relation to the input polarization state) converts the polarization state into intensity [72, 74]. Therefore, in such type of sensors, a change in polarization is translated into a variation in intensity. Using correlation between the change in the output intensity and the measured parameter, a polarimetric fiber sensor is produced for a variety of applications [72, 74].

2.4.2 Typical Sensing Applications

As for most OFSs, polarimetric OFSs can be implemented to measure strain, temperature, corrosion, pressure, among others [72, 73, 75, 76].

Additionally, polarimetric OFSs can further be used to measure current and voltage, using a variety of polarization-based effects, including optical activity, electro-optic effect and Faraday effect [72, 74].

Structural health monitoring (SHM) has always been a hot topic, due to the use of composite materials and the dangers associated with collapsed structures. Lately, with the progress in technology and the advances in Internet of Things (IoT) fields, specifically smart cities, the concept of the so-called “smart” composite structures with compact integrated sensors has become a possibility. Polarimetric OFSs perfectly fit the requirements for deployment in such structures [72].

In composite structures, the monitor of the thermal expansion behavior is of critical importance; hence monitoring such physical parameter is of critical necessity to avoid the debonding induced by differential thermal expansion stresses. A wide range of polarimetric sensors can be used by employing polarization maintaining (PM) and micro-structured highly bi-refringent (HB) polarization maintaining fibers. Such sensors are capable of sensing multiple parameters, such as temperature, strain, displacement and rotation [75, 77].

Temperature variation induces composite material thermal elongation, which is the result of a combination of multiple factors including thermal strain, caused by thermal expansion, induced by moisture absorption, or induced by residual strain [75, 77].

The composite material thermal elongation applies stress to the polymeric fiber sensors, resulting in a significant phase change. By measuring the phase shift and determining the strain sensitivity of the polymeric fiber sensors in constant temperature settings, the strain induced by the thermal elongation can be derived over the sample length [77].

Polarimetric OFSs are advantageous in SHM field, as one such sensor typically only employs a single high-birefringence (HB) fiber for sensing and returns the integrated strain over the sensing region [75]. When compared to ‘point-based sensors’, the HB fiber is sensitive to perturbations over its entire length. Data about damage at multiple points can be recorded; hence providing a more integral and better indication of the severity of damage compared to conventional point-based sensors [75]. Polarimeteric OFSs are also more flexible and easily distributed (can be implemented in surface or internally embedded in structures with minimum effect), lightweight, and with very high sensitivity, while effectively separating effects of external stimuli [72, 75].

2.5 Distributed Optical Fiber Sensors

Distributed sensing refers to the concept, where the fiber itself is the sensing element, and the sensing can be made along the whole length of the optical fiber. Therefore, the parameter under study can be continuously monitored along the overall length of the fiber as a function of time. Figure 2.4 demonstrates such application.

Brillouin, Rayleigh and Raman are three different types of scatterings, famous for the production of distributed optical fiber sensors (DOFSs). The three different scattering types are formed through the interaction of the optical signal carriers with local material properties shift like density, temperature and strain [78].

For instance, if an acoustic/mechanical wave passes through a fiber, a dynamic density change would be generated; such change may be affected by strain, temperature, vibration or birefringence. If changes in the light scattered along a fiber (frequency, phase, amplitude) can be detected, a distributed fiber sensor is then created to access localized oscillation of parameters such as strain, vibrations, temperature, or birefringence, with an action range varying from just few meters all the way up to one hundred kilometers. Such measurement can be realized in the time domain or frequency domain [78, 79]. The produced sensors can be used for disaster prevention in civil structures, through the continuous monitoring of bridges, pipelines, railroads, dams among others [80].

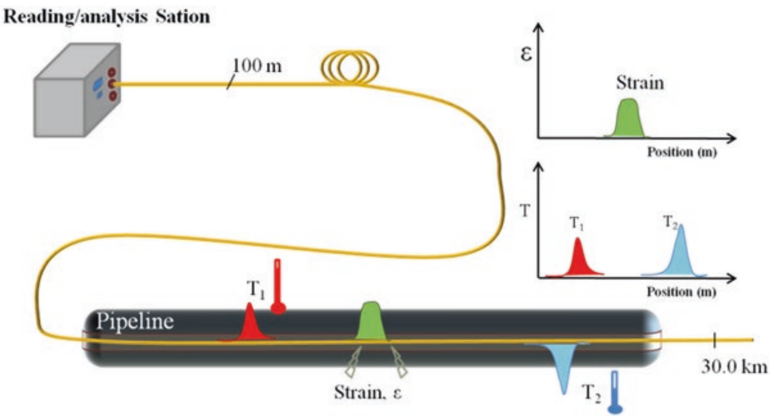

Fig. 2.4 Distributed optical fiber sensing application

A distributed optical fiber sensor is required to return the information on the values of temperature, strain and vibration, from any location along an optical fiber, based on the light scattered along it [78, 80].

Hence its sensing capabilities are distributed over the whole length of the fiber. The challenge is to determine the value of the monitored parameter at exact points along the fiber length, with the required sensitivity and spatial resolution. DOFSs have met such requirement, by providing high performance distributed strain or temperature sensors, which are adequate for applications that cover large areas with relevant location accuracy [78].

For instance, Brillouin-based DOFS specifically provides strain resolution in a few micro-meters range over one meter (micro-strain) and temperature resolution reaching less than 1 °C [79]. Standard communication fibers can be easily embedded in civil structures (bridges, dams, power plants, buildings, airplanes, etc.), to monitor the internal wellbeing status of those structures [78].

2.5.1 Production Methods

As mentioned above, the distributed sensing is performed by connecting the scattering mechanisms with reflectometry techniques in either the time or frequency domain. When used in the time domain, it is referred to as optical time domain reflectometry (OTDR), whereas the frequency domain type is called optical frequency domain reflectometry (OFDR) [78].

Different scattering mechanisms can be invoked when coupling an electromagnetic wave into a silica wave-guide, as shown in Fig. 2.5.

Raman scattering can be produced using such method of coupling an electromagnetic wave into a silica wave-guide. Such method is capable of providing a precise measurement of temperature [81]. Such method of producing Raman scat-

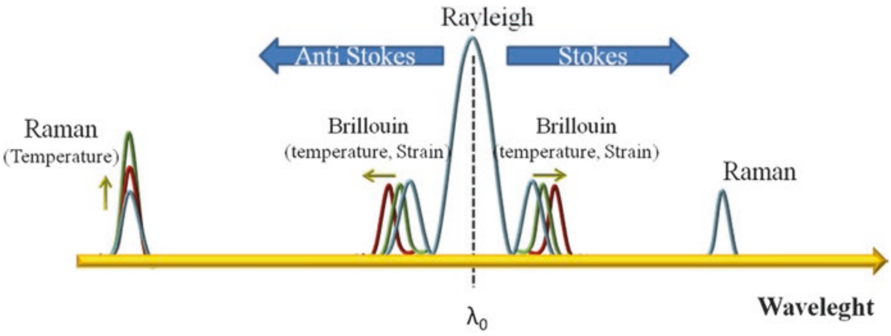

Fig. 2.5 Different possible scattering mechanism observed over the optical signal propagation on an optical fiber

tering is called the spontaneous process and the sensing fiber can be either a single-mode or multimode optical fiber. By measuring the anti-Stokes scattered radiation, the Raman scattering presents itself as a perfect solution for distributed sensing of temperature [81]. This distributed sensing is also advisable for industrial applications requiring high precision, since it has very low sensitivity to other physical parameters such as pressure or strain, dodging its joint influence in the fiber.

Distributed sensing analysis is provided by a light change in the Optical Time Domain Reflectometry (OTDR) receiver to produce a band-pass filter able to separate the Stokes from the anti-Stokes components [78]. The temperature measurement is derived from the ratio between the Stokes and anti-Stokes components, meaning that simultaneous OTDR traces must be obtained for both components; hence a dual channel receiver should be used [79, 81]. Additionally, high transimpedance gain is required for such type of receivers and the bandwidth has to be constrained due to the low level of Raman backscattered signals [78].

The second type of scattering is the Brillouin scattering, which can be formed through the interaction of the incident optical signal and acoustic wave in the material [79]. The thermoelastic oscillation of the optical fiber core constituent molecules results in random density fluctuations, which propagate along the fiber in random directions as acoustic waves. The periodic modulation of density induces a refractive index modulation, which is typically small, but yet still causes diffraction of the incident optical signal [79].

The movement of the density modulation (along with the refractive index grating) at an acoustic velocity induces a frequency shift in the scattered light due to the Doppler Effect: the spontaneous Brillouin scattering. If the spontaneous scattering is intense enough, the incident and the scattered signals interfere, intensifying the acoustic waves. This constructive interference increases the strength of the refractive index grating, resulting in a high intensity of the scattered optical signal [80].

The acoustic wave propagation characteristics are directly related to the optical fiber material density, which in turn is affected by the influence of the medium and by parameters such as strain and temperature. Based on that principle, Brillouin scattering appears as a suitable solution to monitor parameters, such as strain and temperature. Sensing is performed by monitoring the Brillouin backscattered frequency, as the optical interference pulse propagates along the fiber. A major challenge in such production is to accurately access the Brillouin frequency shift. Brillouin scattering also suffers dual sensitivity to strain and temperature; hence there is the challenge of discriminating between the effects of both [78, 79, 80].

2.5.2 Typical Sensing Applications

DOFSs possess multiple characteristics that make them attractive for an array of various applications. First, reduced size sensor (fiber diameter is typically 150 μm) with a spatial resolution of centimeters and high precision in sensing parameters as temperature, vibration, strain, or birefringence is an attractive choice for smart precise applications in smart structures, material processing, and the characterization of optical materials and devices [80].

On another forefront, a wide range of sensing applications would profit from distributed sensing potential of spanning in the special scale up till six orders of magnitude [78, 80]. For instance, distributed temperature sensor (DTS) is one of the most sought-after applications in this domain [78, 81].

The world is currently seeing great progress in the area of renewable energy sources and the installation of smart grid systems, where power distribution becomes extremely dynamic. With such varying environment, it becomes crucial to monitor the conditions of the power cables [81, 82].

One way to monitor power cables is through the insertion of fibers in the inner conductors to measure the temperature, which is used as an indication about the circuit performance. High temperature regions, typically called hot spots in this context, can reduce power transfer capabilities of underground cables. DTSs could perfectly be used in this case to spot the position of those hot spots and help in the dynamic optimization of the power distribution with real-time monitoring. The same concept is also applicable to power cables of submarines [82, 83].

Following the same line of thought, DTSs are also proposed for fire detection in different civil infrastructures such as mines, tunnels, and industrial plants [80]. Those DTSs have already shown high performance, achieving temperature resolution of 5 °C at a distance resolution of about 5 m [83]. Clearly, the alarming thresholds are set depending on the typical ambient conditions. Basically, real-time information obtained from DTSs in concrete structures, submarine installations, oil pipelines, and aircraft wings can provide timely fault diagnostics and continuous evaluation of stress, thus help avoiding disasters and causalities [80, 84].

Another adequate application for DTS is found in the oil and gas industry, where DTSs can be used to indicate geothermal oscillations through temperature monitoring specifically for down-hole monitoring [78].

Alternatively, distributed strain sensing has been widely investigated for deployment in different applications, since its first demonstration in the late 1990s [85].

Reliable structural monitoring has been one of such applications, using distributed sensing in wide civil structures for preventive maintenance. An example deployment can be found in the Gotaalv bridge (1939), Sweden. Distributed strain sensors were used to keep track of the fatigue in the steel girders due to aging, by detecting cracks wider than 0.5 mm [83, 86].

Moreover, in addition to the fiber length instrumentation, the multi-parameter sensing capability is an even more attractive solution, where the same sensing fiber can be used for the monitoring of multiple parameters. Nevertheless, the resolution range and sensitivity requirements of a measurement differ from one application to another, rendering it impossible to find a universal instruction manual for the design of multi-parameter sensors [83].

Distributed sensors can also be used in optical fiber communications, where measurements of the optical fiber polarization spatially resolved properties are needed, and whose results may provide the guideline for the design and manufacturing of low polarization mode dispersion (PMD) fibers for speed communication systems [78].

In conclusion, it is clear that distributed sensing is highly required, when monitoring certain physical parameters as strain, temperature, and vibrations. DOFSs are highly adequate to fill the gap for such demand, due to its unique combination of low loss and sensitivity to those physical parameters. However, those advantages do not come that easy. The production of distributed OFSs requires overcoming certain challenges in order to provide a cost-effective and practical sensing system. The first challenge is instrumentation issue, such as spatial resolution or dynamic range [83]. As all optical fiber based sensors, DOFSs have to be produced such that they are able to discriminate between effects of different physical parameters, such as strain and temperature [79]. Finally, appropriate encapsulation has to be designed in order to provide intimate contact with physical structures (to achieve high sensitivity), but also to be protected from harsh environments that may reduce their efficiency [78, 80, 83].

2.6 Summary

The basic concepts of optical fiber sensing have been introduced in Chap. 1, along with the explanation of the different types of techniques used for OFSs. This chapter provides another step forward, by providing more details about the different types of manufactured OFSs. The production processes of the different types of OFSs are discussed. The chapter covers the different techniques of optical fiber sensing, namely intensity-based, phase-based (or interferometers), wavelength-based, polarization-based, and distributed optical fiber sensors. Different production methodologies are described for each sensor type. The challenges existing in productions processes are pointed out. Additionally, for each type of sensing technique, the most common applications are listed. Multiple applications are named per sensing type, while more than one sensing type can measure the same physical parameters. The chapter also highlights the sensitivity and performance ranges of each sensing type, while emphasizing their limitations.

This chapter presents a survey of the production methods of different types of OFSs. Readers interested in learning how to produce different types of sensors can find this knowledge, along with which sensing type is possible to use for their application and based on their setup and requirements.

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